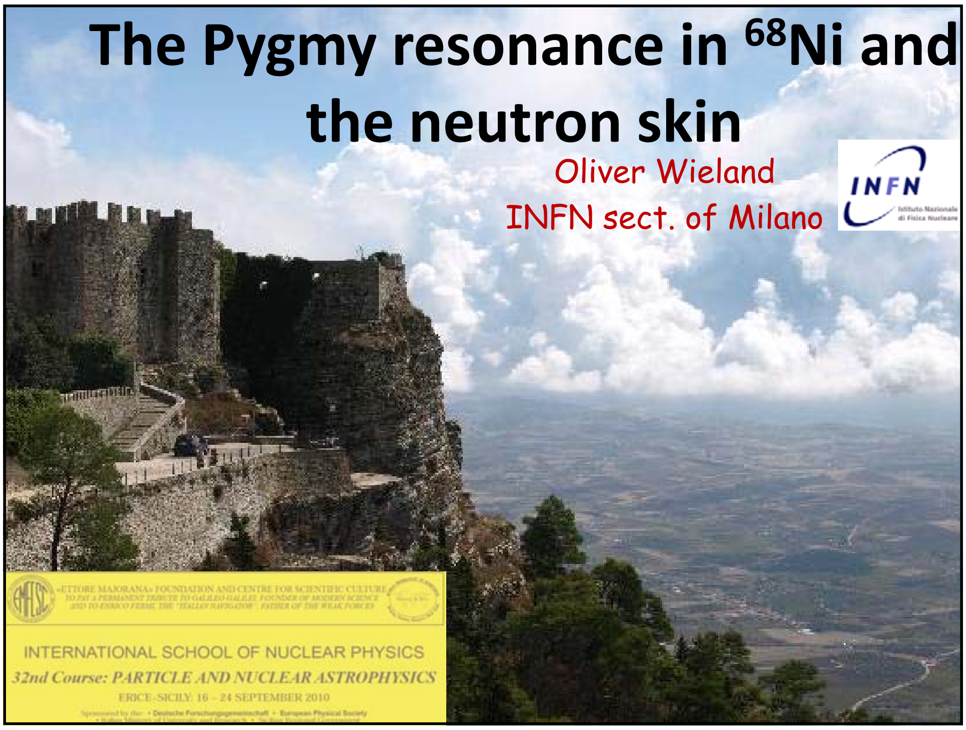
The Pygmy resonance in ^{68}Ni and the neutron skin

Oliver Wieland
INFN sect. of Milano



OUTLINE

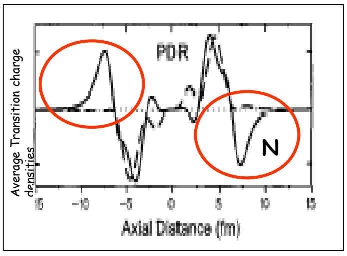
- Motivation
- Experiment description
- Results
- Comparison with theory
- Conclusions and perspectives

RISING @ GSI

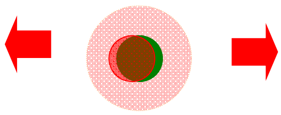
@ GSI

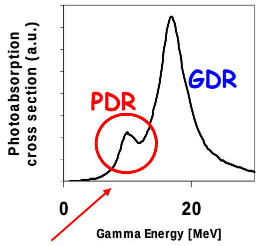
The Pygmy Dipole Resonance (PDR) in neutron rich nuclei (^{68}Ni)

Simple picture: More or less Collective (coherently) oscillation of (loosely bound) **neutrons** (skin) against the core



Richter NPA 731(2004)59



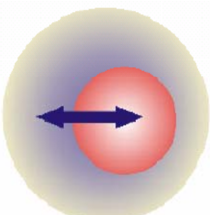


E1 strength **shifted** towards low energy (PDR centroid energy depends on the thickness of n-skin)

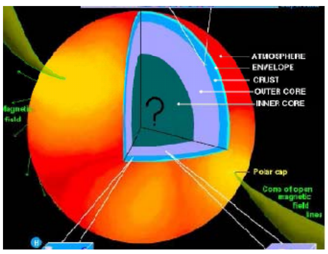
GDR Centroid: Symmetry Energy – length of oscillation axis

Why the Pygmy Resonance is important ?

1 One needs an extrapolation of 18 orders of magnitude
To go from the neutron radius of a nucleus to that of a neutron star (10 fm → 10 km)



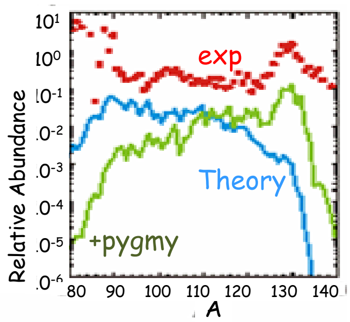
BUT both radii depend on the knowledge of the **equation of state** of neutron rich matter.



2 Pygmy Resonance may have an important impact on the r-process nucleosynthesis

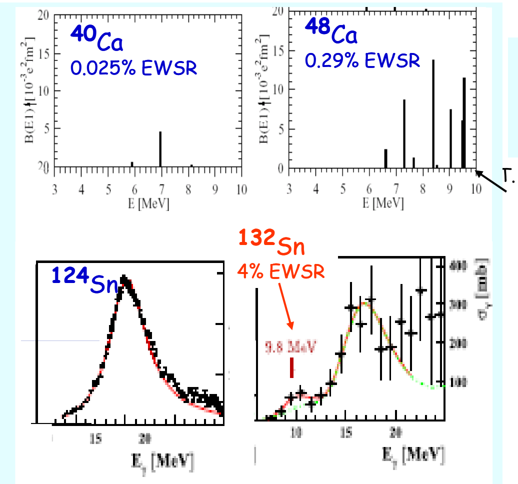
S.Goriely, Phys. Lett. B436 10 (1998)
S.Goriely and E. Khan, Nucl. Phys. A706 (2002) 217
…

3 how **collective properties** change with **neutron** number



Features of this mode

There is a trend of the strength to increase with the proton-to-neutron asymmetry



Stable nuclei ⇒ photon scattering,Photoabsorption (γ,γ '),(γ,n)...

T. Hartmann PRL85(2000)274

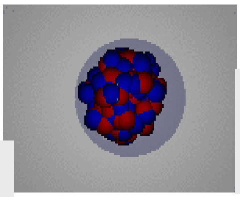
Adrich et al. PRL 95(2005)132501

Exotic nuclei

Virtual photon breakup

LAND experiment

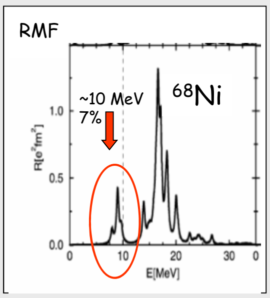
Search for pygmy strength in ^{68}Ni in theory



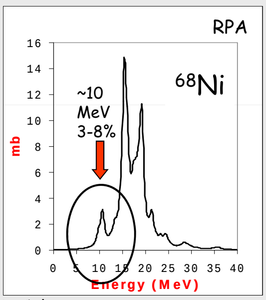
n excess vs inert core : oscillation of the neutron skin

Different approaches give similar predictions in terms of collectivity, strength and line-shape of the pygmy resonance

Theoretical Predictions Before the experimental results



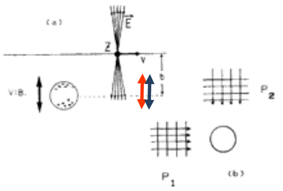
D. Vretnar et al. NPA 692(2001)496

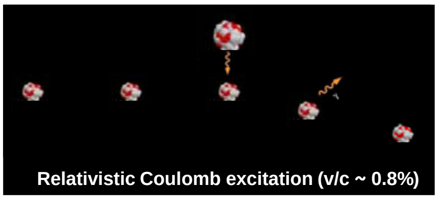


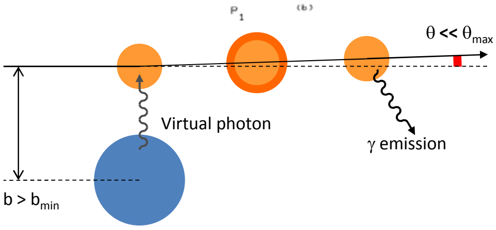
G. Colo private communications

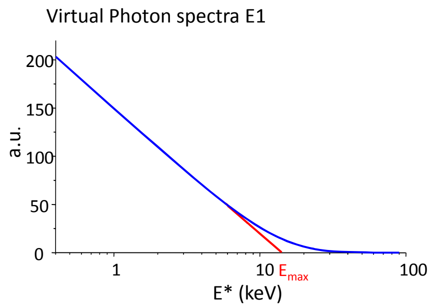
+ J. Liang et al., PRC75(2007) fRPA: 7-8%:

Virtual photon scattering technique (1)









$$\frac{d\sigma_C}{dE^*} = \sum_{\pi\lambda} \frac{1}{E^*} N_\gamma^{\pi\lambda}(E^*) \cdot \sigma_\gamma^{\pi\lambda}(E^*)$$

$$E_{\max} = \frac{\beta\gamma}{b_{\min}} \hbar c$$

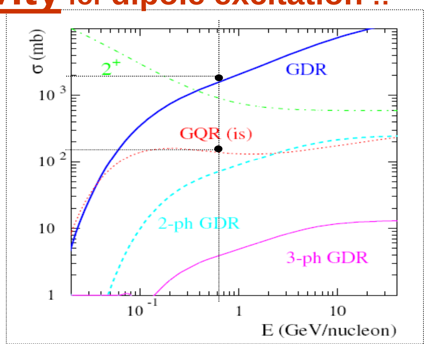
Virtual photon scattering technique (2)

•ADVANTAGE: High selectivity for dipole excitation !!

GDR + PYGMY Excitation

$^{197}Au(^{68}Ni,^{68}Ni^*+\gamma)^{197}Au$

600 MeV/u ^{68}Ni + ^{197}Au (April 2005)
400 MeV/u ^{68}Ni + ^{197}Au (May 2004)



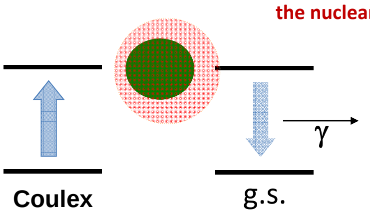
T.Aumann et al EPJ 26(2005)441

$$\frac{\sigma(GDR)}{\sigma(GQR)} \approx 20$$

Virtual photon excitation
and decay of **GDR + PYGMY**

→At large energies the cross section for the Coulomb excitation of the GR overcomes the nuclear geometrical cross section!

maximum excitation
energy (adiabatic cut off)
ca. E*max=18.5 MeV



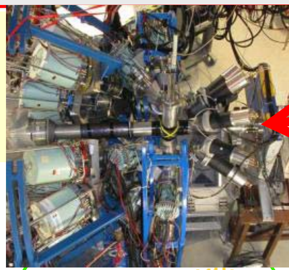
GDR Ground state decay branching ratio
~ 2% measured on ^{208}Pb

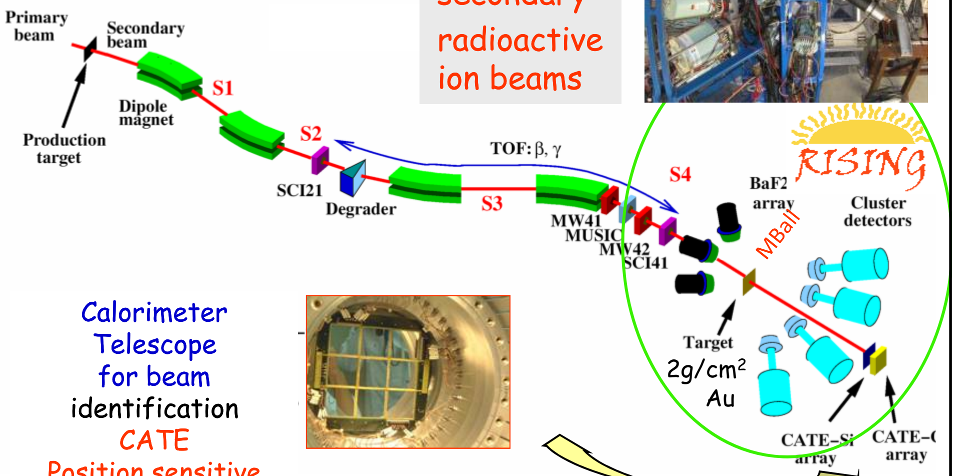
[Beene et al PRC 41(1990)920]

High resolution γ-spectroscopy at the FRS of GSI

- ^{68}Ni beam by fragmentation of ^{86}Kr @ 900 MeV/u on Be target (4g/cm^2):
- 10^{10} ppspill ^{86}Kr, Spill length 6s,period 10 s

FRS provides secondary radioactive ion beams





Calorimeter Telescope for beam identification CATE Position sensitive

Coulomb excitation of ^{68}Ni @ 600 AMeV

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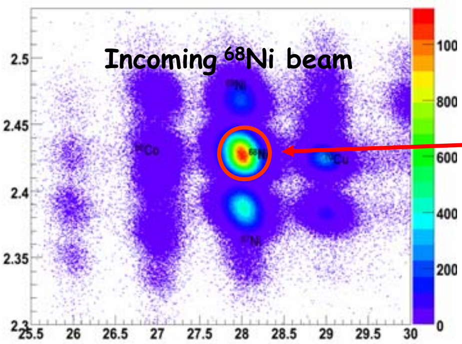
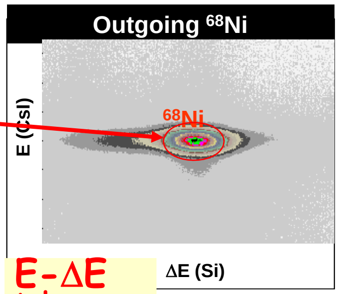
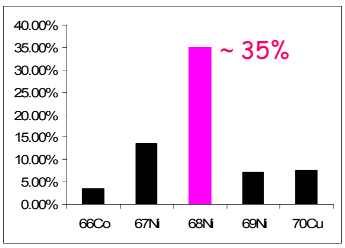


GATE



E-ΔE telescopes



~ 6 Days of effective beam time
~ 400 GB of data recorded

~ $1 \cdot 10^8$ 'good ^{68}Ni events'

Incoming+Outgoing ^{68}Ni

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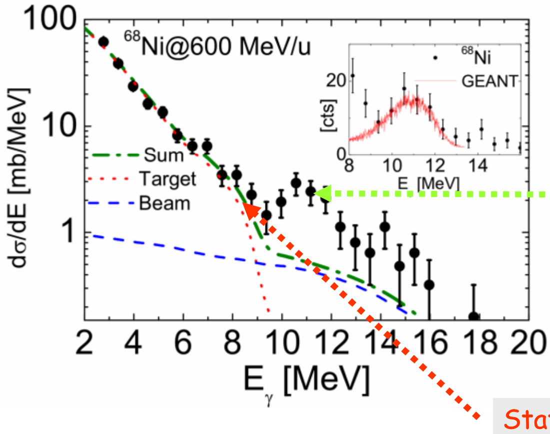
γ-rays spectrum of BaF_2 detectors



an excess yield due to beam emission !!

Statistical emission of γ-rays from :
target nuclei (^{197}Au)
beam nuclei (^{68}Ni)

folded with Response Function including Doppler correction!

Conditions:
- ^{68}Ni-incoming-selection
- ^{68}Ni-outgoing-selection
- TOF-in prompt
- Outgoing angle check
- Doppler correction
- mg=1
- Detector specific (PSA, AddBack)

ANALYSIS: ground state gamma-ray decay from a GR state following a Coulomb excitation

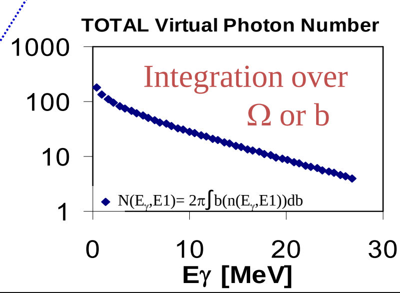
The measured γ-ray yield is due to the product of 3 terms:
Virtual photon N, photoabsorption cross sect, Branching

$$\frac{d^2\sigma_{C\gamma}}{d\Omega dE_\gamma}(E_\gamma)=\frac{1}{E_\gamma}\frac{dn_\gamma}{d\Omega}(E_\gamma)\,\sigma_\gamma(E_\gamma)\,R_\gamma(E_\gamma).$$

[… Beene, Bortignon, Bertulani …]

! Coulomb excitation probability is directly proportional to the Photonuclear cross section

[Eisenberg,Greiner, Bertulani,Alder,Winther,…]



ANALYSIS:

The measured gamma yield for Coul-ex has a cross section directly proportional to the :

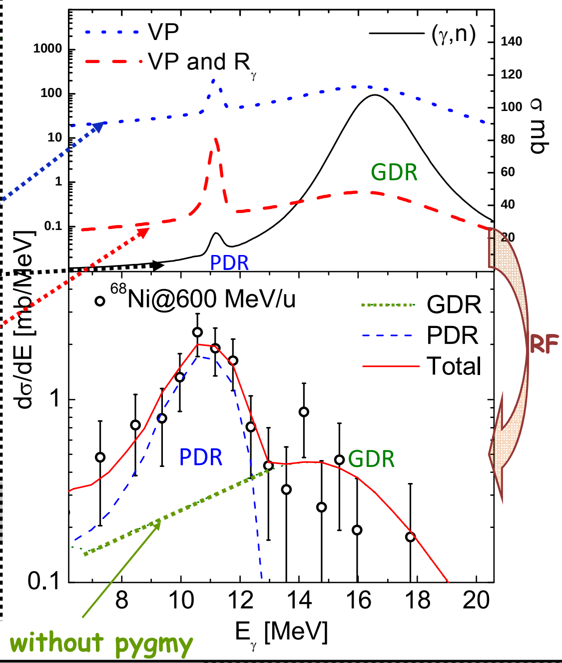
Photonuclear cross section

virtual photons

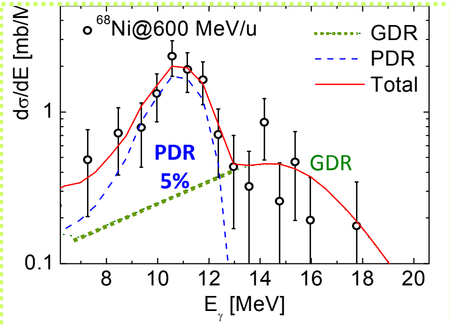
Gamma branching

$$\frac{d\sigma_{C\gamma}}{dE_\gamma} = RF\left\{\frac{1}{E_\gamma} N_\gamma(E_\gamma)\cdot\sigma_\gamma(E_\gamma)\cdot R_\gamma(E_\gamma)\right\}$$

Response Function



RESULT: Pygmy dipole resonance in ^{68}Ni



O. Wieland et al., PRL102(2009)092502

Pygmy in ^{68}Ni at 11 MeV

Width ≈ 2 MeV mainly due to Doppler Broadening

5 (±1.5) % of the EWSR

B(E1) = 1.2 e^2fm^2

Next steps :

- Compare strength with Sn data
- Compare with theory
- Deduce the Neutron radius
- Deduce Symmetry energy and
- Compare with fragmentation results

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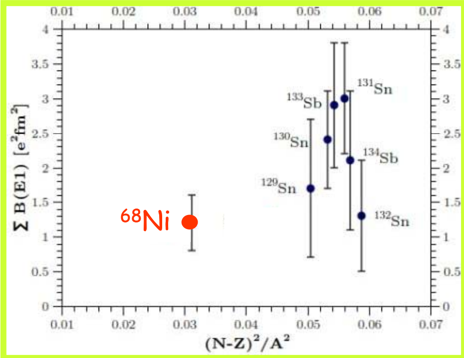
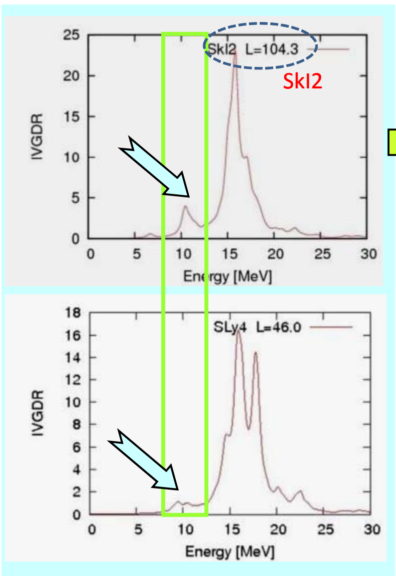
Compare the strength in ^{68}Ni with Sn data

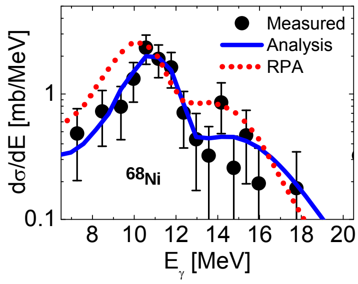


- Lower value of the B(E1) in ^{68}Ni as compare to the Sn region
- This is consistent with the fact that $(N-Z)^2/A^2$ is smaller
- $(N-Z)^2/A^2$ governs the symmetry energy in finite nuclei

This is the first hint that from the strength of the pygmy one could get information on the symmetry energy

Compare strength of pygmy in ^{68}Ni with theory





Note that the shape and strengh depends on the effective force

Calculations of different types are available:

- ❑ Microscopic Hartree-Fock + random phase approximation
- ❑ Relativistic Quasi particle Random Phase approximation

Associated EOS quantities

Nuclear matter EOS | Symmetric matter EOS | Symmetry energy S

The symmetry energy is associated with the exchange of protons into neutrons, and E/A in neutron matter is E/A in symmetric matter plus S !

$$\frac{E}{A}(\rho,\delta) = \frac{E}{A}(\rho,\delta=0) + S(\rho)\,\delta^2 \quad \text{where } \delta = (\rho_n - \rho_p)/\rho$$

The density dependence of the symmetry energy is poorly constrained and one would like to know the key parameters

$E(\rho,\delta) = E_0(\rho,\delta=0) + S(\rho)\delta^2 + O(\delta^4)$

$\delta = (\rho_n - \rho_p)/\rho = (\rho_n - \rho_p)/(\rho_n + \rho_p)$

$S(\rho) = J + L/3\ ((\rho - \rho_0)/\rho_0) + K_{sym}\,((\rho - \rho_0)/\rho_0)^2 + \ldots$

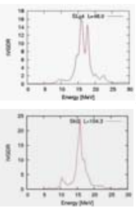
Expansion around density

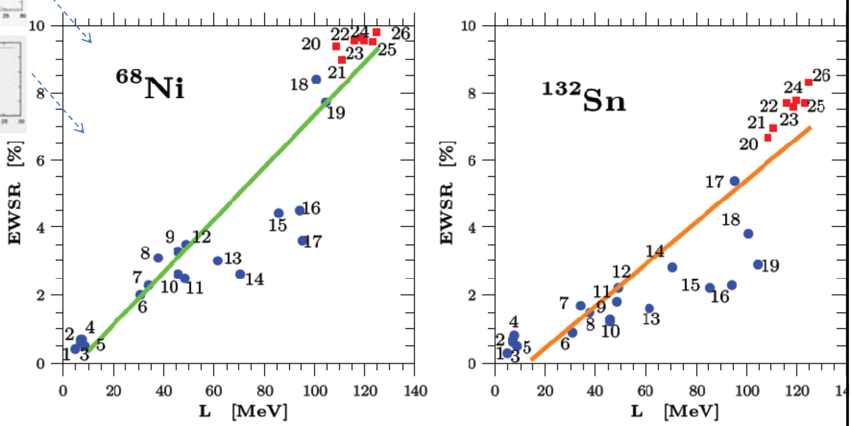
ρ_0 = saturation density

L slope parameter K_{sym} curvature parameter at saturation density

$$\text{where}\quad S(\rho_0) = J,\quad S'(\rho_0) = L/3\rho_0,\quad S''(\rho_0) = K_{sym}/9\rho_0^2$$

Correlation between L and the PDR





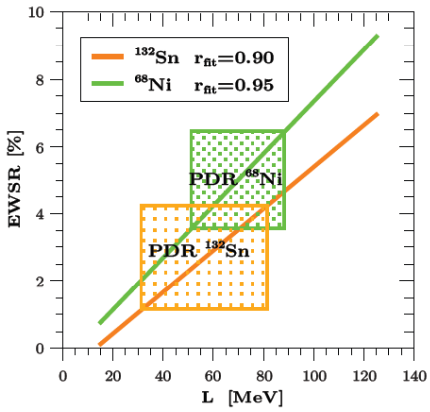
The idea has been previously presented, and exploited in part.

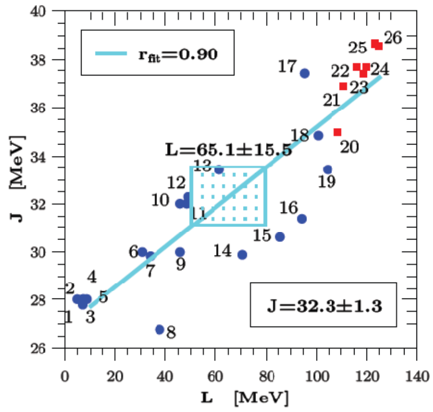
However, here for the first time the approach has been pursued with different nuclei and different classes of EDFs. Blue=Skyrme; red=RMF.

Constraint on J and L

We deduce the weighted average for L
→ then, J under that constraint

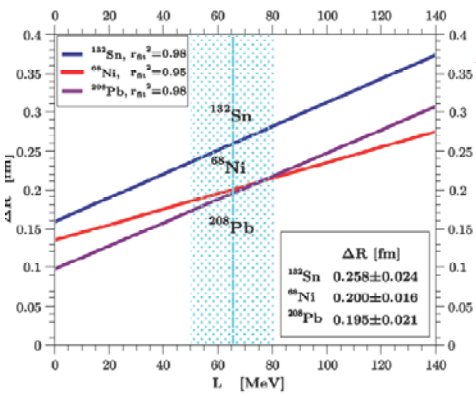
Exp. values from O. Wieland *et al.*, PRL 102, 092502 (2009); A. Klimkiewicz *et al.*, PRC 76, 051603(R) (2007).





J and L for ^{68}Ni and ^{132}Sn
From the L value deduced one gets the J value
30< S_0<34 from Sn analysis
of ref PRC76(2007)051601

Extract the neutron radius for ^{208}Pb



Strong correlations between L and ΔR (the neutron skin thickness) have been noticed previously.

B.A. Brown, PRL 85, 5296 (2000); S. Typel and B.A. Brown, PRC 64, 027302(R) (2001).
R.J. Furnstahl, NPA 706, 85 (2002);
S. Yoshida and H. Sagawa, PRC 69, 024318 (2004).

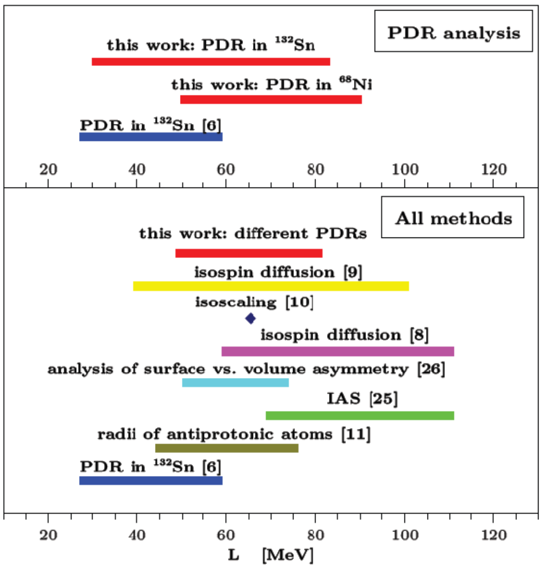
Use the L value from the analysis of the exp of ^{68}Ni and ^{132}Sn

and using the value of L deduced from ^{68}Ni and ^{132}Sn for ^{208}Pb one obtains

R_n-R_p = 0.195+/- 0.021 for ^{208}Pb

The analysis of Klimkiewicz based on ^{132}Sn data gave for ^{208}PB
R_n-R_p = 0.18 +/- 0.035 for ^{208}Pb

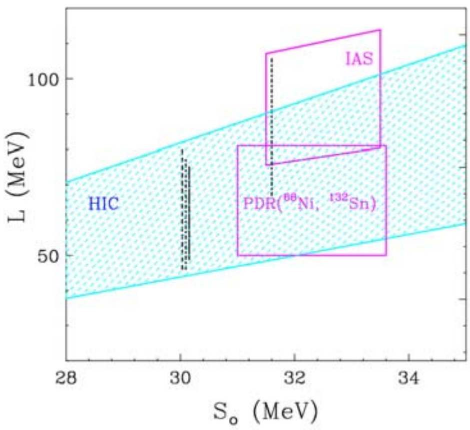
Comparison with other ways of constraining L



Our general approach of extracting L from the PDR makes its value compatible with those from analysis of heavy-ion collisions.

Comparison with heavy ions fragmentation reactions

Two different analysis and measured quantities give consistent constraints to the symmetry energy !



Constraints on the Density dependence of the Symmetry Energy

Measurements from collisions Involving ^{112}Sn and ^{124}Sn with improved quantum molecular dynamics transport model

M.B. Tsang et al. PRL102(2009)122701 + this analysis

Isospin effects in Heavy Ion Collisions (HIC)-Method and Energy of Isobaric Analogue State (*IAS*)-Method

Conclusions + Perspectives

- Pygmy resonance for the first time with virtual photon scattering technique in ^{68}Ni
- Combined analisysis with ^{132}Sn
  → neutron skin radius deduced

+

- More neutron rich nuclei (strengh at lower energy below neutron binding and larger neutron skin radia??)
- Finite temperature – interesting perpectives but higher intensity are needed for this method
- Proton rich nuclei ?
- Even odd nuclei

Thanks for the attention !!

RISING PYGMY Collaboration

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Analysis using theory…….
A.Carbone, P.F. Bortignon, A. Bracco, F. Camera, G. Colò, O. Wieland (University of Milano and INFN)
Phys. Rev. C 81 (2010) 041301(R)

Extra slides

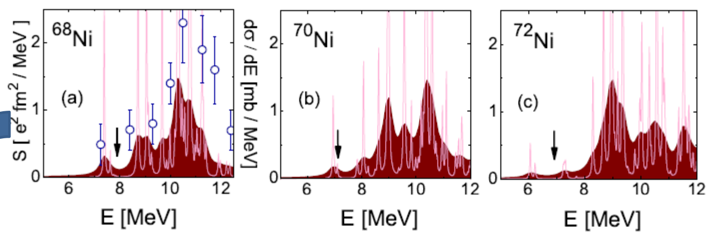
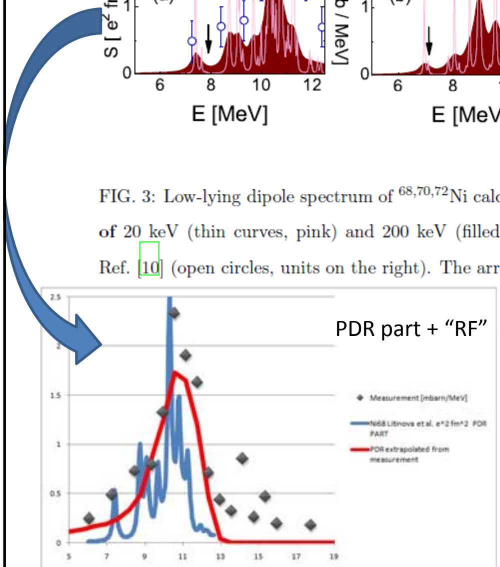


FIG. 3: Low-lying dipole spectrum of ^{68,70,72}Ni calculated within the RQTBA-2 with **a smearing of** 20 keV (thin curves, pink) and 200 keV (filled area). Panel (a) contains also the data from Ref. [10] (open circles, units on the right). The arrows show the neutron thresholds.



Elena Litvinova, Peter Ring and Victor Tselyaev 2009

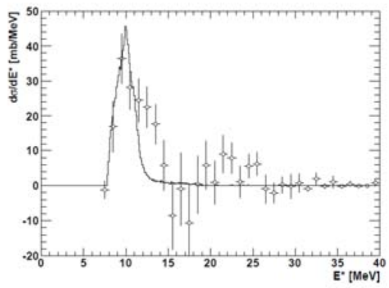


Figure 6.18: PDR distribution fit to excess ^{68}Ni Coulex cross section. The data points are the measured values after subtraction of the GDR distribution.

PHD Thesis **2010** D.Rossi LAND group @ GSI

"…. Allows the conclusion that low-lying dipole strength has been observed in the present experiment, and that the PDR strength of ^{68}Ni is of the order of 5 to 10% of the TRK sum-rule strength."